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Individual Global Navigation Satellite Systems in the Space Service Volume

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Abstract

Besides providing position, navigation, and timing (PNT) to terrestrial users, GPS is currently used to provide for precision orbit determination, precise time synchronization, real-time spacecraft navigation, and three-axis control of Earth orbiting satellites. With additional Global Navigation Satellite Systems (GNSS) coming into service (GLONASS, Beidou, and Galileo), it will be possible to provide these services by using other GNSS constellations.

The paper, "GPS in the Space Service Volume," presented at the ION GNSS 19th International Technical Meeting in 2006 (Ref. 1), defined the Space Service Volume, and analyzed the performance of GPS out to 70,000 km. This paper will report a similar analysis of the performance of each of the additional GNSS and compare them with GPS alone.

The Space Service Volume, defined as the volume between 3,000 km altitude and geosynchronous altitude, as compared with the Terrestrial Service Volume between the surface and 3,000 km. In the Terrestrial Service Volume, GNSS performance will be similar to performance on the Earth's surface. The GPS system has established signal requirements for the Space Service Volume.

A separate paper presented at the conference covers the use of multiple GNSS in the Space Service Volume.

Acronyms

AGI	Analytical Graphics, Inc.
GEO	geosynchronous Earth orbit
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HEO	highly elliptical orbit
IOV	in orbit validation
LEO	low Earth orbit
MEO	medium Earth orbit
NASA	National Aeronautics and Space Administration
PNT	Position, Navigation, and Timing
PVT	Position, Velocity, and Timing
SCaN	Space Communication and Navigation
SSV	Space Service Volume
STK	Systems Tool Kit (formerly Satellite Tool Kit, Analytical Graphics, Inc.)
TSV	terrestrial service volume

Introduction

Although GNSS were created to provide position, velocity and timing (PVT) for terrestrial applications, they can also provide PVT to Earth orbiting satellites. GPS is already being widely used for this purpose, having first flown onboard Landsat 4 in 1982 (Ref. 2).

For satellites operating in low Earth orbit (LEO), GNSS receivers will see signal that are similar to those seen by terrestrial users, apart from the high dynamic effects due to orbital velocity. They can receive signals through a zenith-pointing antenna because they are within the primary transmitted beam of the GNSS satellites. For GNSS use, LEO extends to beyond 3,000 km.

For satellites in higher orbits, a zenith-pointing antenna can receive fewer signals, since the satellite will be outside the main beam of many satellites. Above GNSS altitude, of course, the number of signals received from above the satellite will be zero. However, GNSS can still be used for PVT at these altitudes by taking advantage of tracking GNSS signals crossing the Earth's limb using a nadir-pointing antenna, as shown in Figure 1, while satellites at intermediate altitudes can use a combination of zenith- and nadir-pointing antennas. Due to the increased range and reduced transmitter gain at the larger off-nadir angles, the signals will be much weaker than those available at the Earth's surface. However, specialized GPS receivers have demonstrated the increased acquisition and tracking sensitivity and integrated a navigation filter for state estimation when less than four satellites are available. Multi-constellation GNSS receivers for satellites are currently under development.

Space Service Volume

Based on the unique nature of GNSS signals as a function of altitude, requirements for GNSS spacecraft services can be allocated to two service volumes. The terrestrial service volume (TSV) includes all terrestrial and space GNSS users up to an altitude of 3,000 km, and the space service volume from 3,000 km to the approximate geostationary altitude of 36,000 km.

Terrestrial Service Volume

Users in the TSV enjoy uniform received powers and have fully overlapping coverage. The use of multiple GNSS will

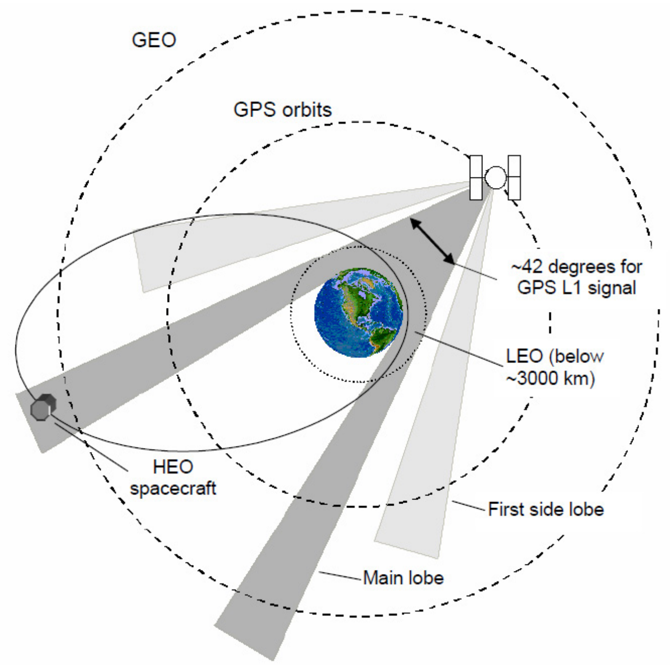

Figure 1.—Geometry for reception of GNSS signals by a HEO satellite (Ref. 1).

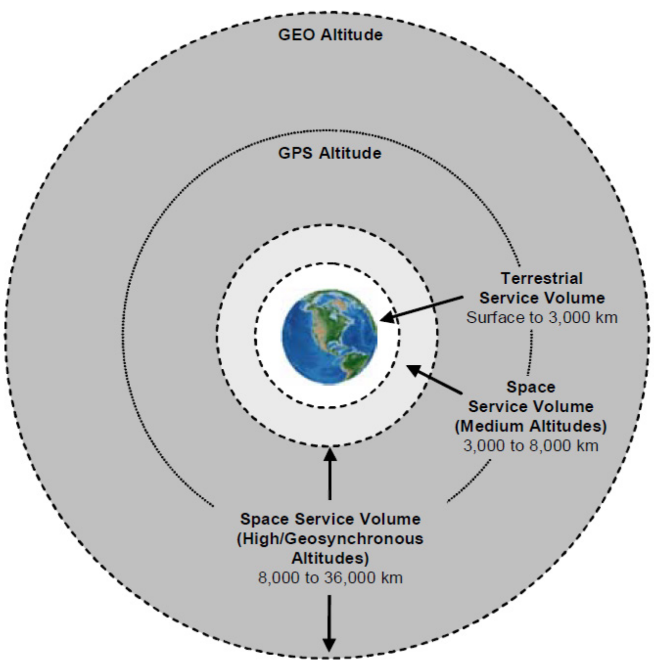

Figure 2.—Terrestrial and Space Service Volumes (Ref. 1).

have some benefit due to the increased number of pseudoranges available although individual GNSS already provide very good coverage.

Space Service Volume

The SSV can be divided into two regions: (1) the medium Earth orbit (MEO) SSV (3,000 to 8,000 km), and (2) the HEO/GEO SSV (8,000 to 36,000 km). Figure 2 illustrates the relationship between the three altitude regions described above. In the TSV, adequate coverage can be supplied by a zenith-pointing antenna; in the MEO region, a combination of zenith- and nadir-pointing antennas are needed, but even a single GNSS will often provide four-satellite coverage; in the highly elliptical orbit (HEO)/geosynchronous Earth orbit (GEO) region nearly all GNSS signal will come from satellites transmitting across the Earth's limb.

Availability of GNSS Services

Currently GPS provides promises of future signal strength and quality within guaranteed beamwidth out to GEO altitude (Ref. 3).

Signal Availability

This section summarizes the analyses of multi-constellation GNSS availability for spacecraft navigation.

STK simulations were used to evaluate the availability of GNSS signals for each of the new systems (GLONASS, Galileo, and Beidou) as well as GPS.

The GPS constellation used in the simulations is the 24+3 constellation currently planned for future availability. The GLONASS constellation is the current 24-satellite constellation. The Galileo constellation is the planned 24-satellite constellation. The Beidou constellation is the 24 MEO satellite portion.

The beamwidths used in the simulation are the committed GPS half-beamwidths of 23.5° for GPS L1 and 26° for GPS L2 and L5 (Ref. 3). Since beam data for Beidou and GLONASS are not available, we assume half-beamwidths of 23.5° for GLONASS L1 and Beidou B1; and 26° for GLONASS L2 and L3, Beidou B2 and B3, similar to GPS beamwidths. The published Galileo IOV antenna data show somewhat narrower beams (appropriate for their higher altitude) so we used 24° for the half-beamwidth of E5 and E6 and 20° for the half-beamwidth of E1 (Ref. 4).

An Earth atmosphere mask was applied requiring signals to pass at least 50 km above WGS84. While ionospheric effects can be important for signals passing less than 1,000 km above the Earth's surface, all GNSS satellites transmit multiple frequency signals through this region allowing multi-frequency receivers to correct for ionospheric effects.

At each altitude, a grid of approximately 2,000 evenly spaced points was generated covering all latitudes and longitudes. For each grid point, the GNSS constellations were propagated forward in time 48 hr (in 60-sec steps) and line of sight vectors were evaluated for each step in time. The products of a run were time histories of GNSS satellites visible. From this availability, statistics were calculated, giving the following metrics listed in Table 1 to Table 8:

- Availability of at least one and of at least four GNSS satellites, both for an average point and for the worst point
- Duration of longest single-fold outages (intervals when no satellite visible)
- Duration of longest four-fold outages (intervals when less than four satellites were visible)
- Minimum, average, and maximum number of satellites visible

TABLE 1.—SIMULATED ALTITUDES

Altitude	Comment
300 km	Typical LEO Altitude
3,000 km	Border between TSV and SSV
8,000 km	Border between medium and high orbit service
15,000 km	Within high orbit service, below GNSS altitude
25,000 km	Within high orbit service, above GNSS altitude
36,500 km	Approximate GEO altitude
70,000 km	Approximately twice GEO altitude

TABLE 2.—A 300 km ALTITUDE

	GPS	GLONASS	Galileo	Beidou
1+ (%)	100	100	100	100
4+ (%)	100	100	100	100
<1 (s)	0	0	0	0
<4 (s)	0	0	0	0
Min. (#)	10	14	12	12
Ave. (#)	14.3	15.2	12.7	12.5
Max.(#)	19	18	17	17

TABLE 3.—A 3,000 km ALTITUDE

	GPS	GLONASS	Galileo	Beidou
1+ (%)	100	100	100	100
4+ (%)	100	100	100	100
<1 (s)	0	0	0	0
<4 (s)	0	0	0	0
Min. (#)	16	15	16	18
Ave. (#)	20.9	18.0	18.7	18.7
Max. (#)	24	22	20	20

TABLE 4.—A 8,000 km ALTITUDE

	GPS	GLONASS	Galileo	Beidou
1+ (%)	100	100	100	100
4+ (%)	99.9+	99.9	100	100
<1 (s)	0	0	0	0
<4 (s)	595	706	0	0
Min. (#)	3	3	4	5
Ave. (#)	9.6	7.5	9034	9.9
Max. (#)	15	12	12	12

TABLE 5.—A 15,000 km ALTITUDE

	GPS	GLONASS	Galileo	Beidou
1+ (%)	99.9+	97.3	98.8	98.6
4+ (%)	80.0	61.6	68.7	75.2
<1 (s)	604	2,395	2,502	2,083
<4 (s)	8,289	7,247	7,581	5,405
Min. (#)	0	0	0	0
Ave. (#)	4.7	3.8	3.6	4.6
Max. (#)	10	9	8	9

TABLE 6.—A 25,000 km ALTITUDE

	GPS	GLONASS	Galileo	Beidou
1+ (%)	99.4	98.7	99.9	99.98
4+ (%)	36.0	19.6	15.8	24.6
<1 (s)	3,158	1,069	414	262
<4 (s)	30,166	28,692	79,839	25,283
Min. (#)	0	0	0	0
Ave. (#)	3.1	2.6	2.7	3.0
Max. (#)	8	6	6	6

TABLE 7.—A 36,500 km ALTITUDE
LOW FREQUENCY SIGNALS

	GPS	GLONASS	Galileo	Beidou
1+ (%)	97.0	94.0	94.9	90.2
4+ (%)	15.6	9.6	5.4	8.0
<1 (s)	9,763	2,194	3,024	1,649
<4 (s)	72,272	Never	Never	Never
Min. (#)	0	0	0	0
Ave. (#)	2.4	2.1	2.0	2.3
Max. (#)	6	6	4	5

TABLE 8.—A 70,000 km ALTITUDE

	GPS	GLONASS	Galileo	Beidou
1+ (%)	89.6	79.9	79.2	85.1
4+ (%)	2.8	4.7	2.4	3.2
<1 (s)	Never	4,013	Never	4,763
<4 (s)	Never	Never	Never	Never
Min. (#)	0	0	0	0
Ave. (#)	1.7	1.4	1.4	1.6
Max. (#)	6	4	4	4

Conclusions and Summary

The results clearly show the increased availability and reduced outage durations from using multiple GNSS for spacecraft PVT at the higher altitudes. At lower altitudes, the increase in number of GNSS satellites in view will allow more accurate PVT, even though the use of multiple GNSS constellations is not necessary to prevent outages.

References

1. Bauer, F. H., et al., "The GPS Space Service Volume," Proceedings of the ION GNSS-2006, Fort Worth, TX, Sept. 2006.
2. Bisnath, S., Spaceborne GPS Information Site, Geodetic Research Laboratory, Department of Geodesy and Geomatics Engineering, University of New Brunswick, http://gauss.gge.unb.ca/grads/sunil/sgps.htm
3. Anon., Global Positioning System Directorate Systems Engineering & Integration Interface Specification, IS-GPS-200 Revision F, Sept. 21, 2011.
4. Monjas, Fernando, et al., "Test Campaign of the IOV (In Orbit Validation) Galileo System Navigation Antenna for Global Positioning," 2010 Proceedings of the Fourth European Conference on Antennas and Propagation (EuCAP).

Biography

Dale A. Force is an electronics engineer at NASA Glenn Research Center studying the use of Global Satellite Navigation Systems for navigating satellites. He received the B.S. and M.S. degrees in Physics from Michigan State University and an M.E. degree in electrical engineering from the University of Utah.